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The effects of salience on saccadic target selection

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Two experiments were conducted to investigate the effects of saliency on saccadic target selection as a function of time. Participants were required to make a speeded saccade towards a target defined by a unique orientation presented concurrently with multiple nontargets and one distractor. Target and distractor were equally salient within the orientation dimension but varied in saliency in the colour dimension. Within the colour dimension, the target presented could be more, equally, or less salient than the distractor. The results showed that saliency played a large role early during processing while no effects of saliency were found in later processing. Results are discussed in terms of models on visual selection.

Imagine yourself in the library looking for a specific book. You know the name of the author and the title, but you have no idea what the book looks like. Assume that on an average day, it takes you about 5 minutes, measured from the point in time you walk into the library, to find an average shaped and coloured book by title and author. It might take you only 1 minute when the book you are looking for happens to be bright red and very large. Many people believe that if a stimulus is sufficiently salient, it will pop out of a visual scene. In turn, they assume that search performance is better when the salient stimulus is the target of search, as compared to when a nonsalient item is the target of search.

Most researchers in the area of visual selective attention assume that covert (attentional) selection and overt (oculomotor) selection are at least partly determined by stimulus salience, or more generally speaking by the stimulus properties in the visual field (Cave & Wolfe, 1990; Itti & Koch, 2000; Koch & Ullman, 1985; Theeuwes, 1991, 1992, 1994; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). To incorporate this idea, recent models of visual selection have proposed that visual selection is determined by the output provided by some common salience map. Within a salience map, the location with the highest activation level corresponds to the most salient location at that point in time and

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will be selected for further processing (Itti & Koch, 2000; Koch & Ullman, 1985). The activation pattern in the map may determine in what sequence an observer selects different locations in space; attention is assumed to be allocated in the order of decreasing activity (Wolfe, 1994). It is generally believed that the activation map only contains information about its location (i.e., where) in the visual field but no information about the source (i.e., what) of activation (e.g., Nothdurft, 2002; Sagi & Julesz, 1985). In the case where visual selection is determined by the stimulus properties in the visual field, selection is generally referred to as exogenous or stimulus driven, or is said to be under bottom-up control.

Apart from the idea that visual selection is determined by the stimulus properties in the visual field, most researchers also assume that the outcome of the saliency map can be modulated by top-down, goal-driven control (Cave & Wolfe, 1990; Itti & Koch, 2001; Wolfe, 1994). However, there is no agreement on how this is exactly accomplished. On the one hand, some have suggested that top-down control may gate visual selection before stimulus-driven information has entered the visual system (Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). On the other hand, others have proposed that top-down control affects selection only after stimulus-driven selection has taken place (Itti & Koch, 2000; Nothdurft, 2002; Theeuwes, 1991, 1992, 1994).

In line with the idea that visual selection is initially under top-down control, various studies have demonstrated that independent of stimulus salience, visual selection can be completely goal driven (e.g., Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Folk, Leber, & Egeth, 2002; Folk & Remington, 1998). Evidence has typically been obtained in cueing studies (Folk & Remington, 1998; Folk et al., 1992, 1994). For example, Folk et al. (1992) performed an experiment in which prior to the presentation of a search display (150 ms) an irrelevant cue was presented at one of four potential target locations. Participants had to indicate the identity of a target (X or =) that was presented as a single onset for one group of participants, or as a colour singleton amongst elements of another colour for another group of participants. The results showed that a spatially incompatible precue interfered with subsequent target identification only when the cue and the target were both defined by the same stimulus property. Cues with task-irrelevant properties did not disrupt performance. Folk et al. argued that whether or not a salient element is selected for further processing strictly depends on the observer's attentional control settings. According to a top-down model of selection, stimulus-driven selection may take place, but only after and contingent upon goal-directed selection. That is, it is assumed that a salient stimulus will only attract the eyes if it shares features with a target an observer is searching for.

Contrary to this top-down account of visual selection, others have suggested that visual selection is initially determined by the stimulus-driven activity pat-

tern in the saliency map (Itti & Koch, 2000; Nothdurft, 2002; Theeuwes, 1991, 1992, 1994). Goal-driven control may play a role, but only after attention is directed to the most salient element in a display. (Nothdurft, 2002; Theeuwes, 1992; Theeuwes, Atchley, & Kramer, 2000). That is, only after an element is selected on the basis of stimulus-driven activity, is an element assumed to be identified and only then may endogenous, top-down modulations be applied. Thus, top-down control is assumed to occur after, and to be contingent, on bottom-up control (Itti & Koch, 2000, 2001; Koch & Ullman, 1985; Nothdurft, 2002; Theeuwes & Burger, 1998).

In line with a bottom-up account of selection (Itti & Koch, 2000; Nothdurft, 2002; Theeuwes, 1991, 1992, 1994), it has been shown that saliency affects search. Saliency may affect search in both a negative or positive manner depending on how saliency is applied in a search display. For example, if the applied saliency is not in line with a set of goals, saliency might hamper search and decrease search efficiency. Thus, Theeuwes (1991, 1992, 1994) showed that if observers have to search for a prespecified target that is unique in a basic dimension (e.g., searching for a diamond shape among circles), the presence of an irrelevant distractor strongly disrupts search if the irrelevant distractor is more salient than the target. Knowledge of the target identity could not override the effect of the presence of an irrelevant salient distractor. Theeuwes concluded that the allocation of attention is ultimately determined by the relative saliency of the stimuli in the visual field.

If, however, saliency is applied in accordance with the task at hand, saliency may improve search performance. For example, Nothdurft (2002) showed that saliency may increase search efficiency. He demonstrated that search for a nonsalient vertical line was slow and reaction times increased with set size. However, when the feature contrast was increased and the target's salience was enhanced, search became fast and independent of set size (Nothdurft, 1993). Thus, saliency may improve search efficiency when it is applied in line with the target. Furthermore, Nothdurft (2002) showed not only that salient targets lead to faster detection but also to faster identification. Observers were faster to identify a salient element than a nonsalient element. Thus, evidence suggests that salient elements may initially guide attentional selection towards a certain location (Wolfe, 1994), by which the target is then recognized (Itti & Koch, 2000; Nothdurft, 2002; VanRullen, 2003). Accordingly, identification is conditioned upon localization. These findings are in line with the idea that top-down control is contingent on stimulus-driven control and suggests that saliency necessarily influences visual selection.

The aim of the present study is to explore the precise role of top-down control on stimulus-driven selection. The aim is to investigate whether top-down control takes place before or after stimulus-driven selection. In other words, is top-down control available early in time in such a way that stimulus-driven selection is contingent on top-down control or is top-down control available only after

stimulus-driven selection has taken place, such that top-down control is contingent on bottom-up control. In addition to these two alternatives however, it may be the case that both types of control operate in a relative independent fashion. In this case, stimulus-driven control may occur before goal-driven control yet in such a way that stimulus-driven selection does not affect goal-driven selection. That is, both manners of control may proceed independently and in different time windows. Evidence for this latter view derives from a recent study by van Zoest, Donk, and Theeuwes (2004). In this study participants were required to make a speeded saccade towards a predefined target presented concurrently with multiple nontargets and possibly one distractor. All elements were defined in the orientation dimension. The target was either more salient, equally salient, or less salient than the distractor. The results showed that the effect of salience critically depended on the time at which a response was elicited. The saliency of the target only affected search when eye movements were elicited early in time. When an eye movement was elicited later in time no effect of saliency was observed. Instead, later in time, eye movements appeared to be increasingly more goal driven. They concluded that visual selection is the outcome of two independent processes, one stimulus driven and the other goal driven, operating in different time windows.

Even though the study of van Zoest et al. (2004) provided evidence for an independent selection model, it should be noted that the salience of the target and the defining property of the target were both determined by variations in the orientation domain. The present study aims to replicate the van Zoest et al. study while manipulating the salience of the target and distractor in a dimension other than the target-defining dimension. Given a task where saliency is completely task irrelevant, a couple of predictions can be made regarding the role of top-down control in visual selection. If goal-driven control is possible prior to stimulus-driven control, it is predicted that saliency should not affect search performance. However, if goal-driven control is conditioned upon stimulus-driven selection, saliency is expected to influence performance. Furthermore, in this case saliency is expected to affect selection regardless of the point in time a response is given. In case of the independent selection model, saliency is expected only to influence selection when attentional selection occurs relatively early in time and not at all when selection occurs later in time based on top-down activation.

Saccadic eye movements were measured in order to investigate how saliency affects target selection.[1] Registration of saccadic eye movements allows for a

[1] Given that ample evidence suggest the existence of a tight coupling between attention and eye movements (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; McPeek, Maljkovic, & Nakayama, 1999; Moore & Armstrong, 2003) a greater understanding in the role of bottom-up and top-down activations in eye movements is expected to lead to a greater understanding of the role of bottom-up and top-down activation in the field of attention.

greater insight in the early stages of processing, as eye movements can be elicited earlier than manual response times (e.g., Ludwig & Gilchrist, 2002). Moreover, saccadic eye movements provide accurate information as to what area in the visual field has been selected. Furthermore, in order to investigate the time course of visual processing analysis was performed separately for the fast and slow saccadic saccadic reponses. Splitting the saccadic eye movements of observers on the basis of time allowed us perspective on the effect of stimulus-driven and goal-directed control on a variety of response latencies.

In the current experiments participants searched for a target defined by a unique orientation among multiple nontargets and one distractor that was also defined by a unique orientation. Target and distractor were equally salient within the orientation dimension. In order to investigate the role of saliency, the colours of the target and distractor were manipulated. Within the colour dimension, either the target or distractor was a unique colour singleton or both elements were of the same colour as the nontargets. As a result, the target could be more, equally, or less salient than the distractor. Note that the saliency was not task relevant.

EXPERIMENT 1

Participants were required to make a speeded saccade towards a prespecified line segment oriented in one direction. The target line segment was presented among multiple vertically oriented nontarget line segments and one distractor. The distractor was a line segment oriented in the opposite direction of the target. Within the orientation dimension, target and distractor were equally salient among the nontargets but maximally different in angle of orientation. There were three possible conditions: Target, distractor, and nontargets were all presented in the same colour (no-colour singleton); only the target was coloured (i.e., target-colour singleton); or only the distractor was coloured (i.e., distractor-colour singleton).

According to a bottom-up control account of visual selection, performance is expected to be higher when the colour singleton involves the target as compared to when the colour singleton involves the distractor. This effect should be present irrespective of the point in time at which a response is emitted. According to a top-down control account of visual attention, the saliency of the target or distractor should not affect performance. The independent timing model of stimulus-driven and goal-driven control would predict that saliency should only affect performance early during visual selection, and that no effects of saliency are present later during selection.

Method

Participants. Thirteen students of the Vrije Universiteit Amsterdam participated as paid volunteers in 50 minute sessions. Participants ranged in age from 20 to 35 and all reported having normal or corrected-to-normal vision.

One person was omitted in the analysis due to poor fixation accuracy prior to the presentation of the search display (>30% of the trials) resulting in a total of 12 participants.

Apparatus. A Pentium II Dell computer with a 21-inch SVGA colour monitor (Philips Brillance 201 P) controlled the timing of the events and generated stimuli. Eye movements were recorded by means of an Eyelink tracker (SR Research Ltd.) with a 250 Hz temporal resolution and a 0.2° spatial resolution. The system uses an infrared video-based tracking technology to compute the pupil centre and pupil size of both eyes. An infrared head motion tracking system was also used. Display resolution was 1024 × 768 pixels. All subjects were tested in a sound-attenuated, dimly lit room with their heads resting on a chinrest. The monitor was located at eye level 75 cm from the chinrest.

Stimuli. Participants performed a visual search task in which they were instructed to make a speeded saccade to a target. The target was defined in the orientation dimension, such that target was a line oriented 45° to the right. Displays consisted of one target, a series of vertical oriented nontargets, and one distractor tilted in the opposite direction of the target (oriented 45° to the left). In one-third of all trials the target was coloured red (CIE x, y, coordinates of .609/ .344; 14.92 cd/m^2), and the distractor white (CIE x, y, coordinates of .288/ .316; 93.14 cd/m^2). In one-third of all trials the distractor was coloured red and the target was white. In one-third of all trials both the target and distractor were white. The vertical nontargets were always white. Elements were presented on a black background. Elements were arranged in a 9 × 13 rectangular matrix with a raster width of 17.06° × 12.63°. Targets and distractors could appear at six different locations. These six potential locations were placed on an imaginary circle in such a way that, embedded in the matrix of nontargets, targets and distractors were always presented at equal eccentricity from fixation (6.1° of visual angle). When a target and a distractor were presented the angular distance between the two elements was always 120° (see Figure 1). Elements had an approximate height of 0.76° of visual angle and approximate width of 0.31° visual angle.

Design and procedure. A within-subjects design was used. Each participant performed 48 practice trials and 540 experimental trials. The three conditions manipulating target–distractor saliency (no-colour singleton, target-colour singleton, and distractor-colour singleton) were mixed.

To start a trial participants pressed the spacebar after which a fixation point was presented for 1000 ms followed by the stimulus array for a further 1500 ms. Participants were instructed to remain fixated until the search display appeared. They were then required to make a speeded saccade to the target while main-

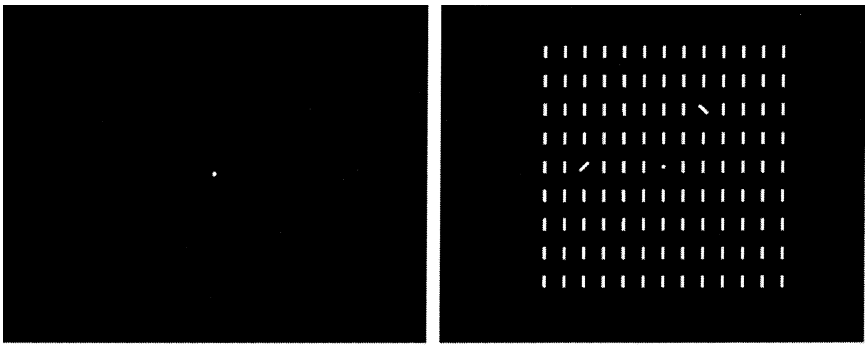

Figure 1. An example of the primary stimulus display.

taining a high level of accuracy. Participants were explicitly told to ignore the distractor if it was presented, and that colour was not indicative of the location of the target. After making an eye movement to the target, participants were instructed to remain fixated on the target until the search display disappeared. To make sure participants understood the task correctly, participants were given both written and oral instruction.

Feedback concerning saccade latency was provided every 30 trials. Participants were free to take a break between the two experimental blocks. Prior to the recording, subjects viewed a calibration display consisting of nine points in a square array, fixated sequentially.

Results

Initial saccade latencies below 80 ms (anticipation errors; 6.5% of trials) and saccade latencies above 600 ms (0.7 % of trials) were counted as errors and were excluded from the analyses. The initial saccade was assigned to a target or distractor if the endpoint of the initial saccade was within 3° of visual angle of the particular target or distractor position. Of the initial saccades 4.1% missed either the location of the target or the distractor and were not analysed further.

Table 1 presents the percentages and the saccade latencies of the saccades directed towards the target or distractor for each target–distractor saliency condition. To examine the percentage of correct eye movements to the target, a within-subject analysis of variance (ANOVA) with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) as factor was performed. A main effect of colour singleton condition was found, $F(2, 22) = 4.55$, $p < .05$. The least number of correct eye movements to the target were made in the distractor-colour singleton condition (mean

TABLE 1
Percentage and saccade latencies (in ms) of the saccades directed towards the target or distractor in Experiment 1

	Condition		
Direction of eye movement	*Target white, distractor white*	*Target red, distractor white*	*Target white, distractor red*
To the target			
Percentage (%)	59.7	66.7	47.6
Saccade latency (ms)	247	226	255
To the distractor			
Saccade latency (ms)	231	238	210

48%), followed by the no-colour singleton condition (mean 60%). Accuracy was highest in the target-colour singleton condition (mean 67%). To examine the effect of target–distractor saliency on saccade latency an ANOVA was performed with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) as the factor. A main effect of colour singleton condition was found, $F(2, 22) = 11.18$, $p < .01$. Saccadic latency to the target was lowest in the target-colour singleton condition (mean 226 ms), followed by the no-colour singleton condition (mean 247 ms). Saccadic latency to the target was highest in the distractor-colour singleton condition (mean 255 ms).

An ANOVA on saccadic latency to the distractor with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) as a factor revealed a main effect of colour singleton condition, $F(2, 22) = 11.66$, $p < .01$. Saccadic latency to the distractor was lowest when the distractor was a colour singleton (mean 210 ms), followed by the no-colour singleton condition (mean 231 ms). Saccadic latency to the distractor was highest when the target was a colour singleton (mean 238 ms).

In order to examine performance as a function of time more closely, the time course of the proportion of correct eye movements directed towards the target was analysed. For each participant, an individual distribution of the initial saccade latencies was calculated irrespective of the saccade destination. Distributions were divided into five quintiles based on saccade latency and the proportion of correct eye movements was calculated for each quintile. For each quintile the average saccade latency was calculated (see Figure 2). An ANOVA was conducted with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) and quintile (5) as factors. A main effect of colour singleton condition was found, $F(2, 22) = 4.51$, $p < .05$, as well as an effect of quintile $F(4, 44) = 12.78$, $p < .01$. An interaction between colour singleton condition and quintile, $F(8, 88) = 11.03$, $p < .01$, indicated that

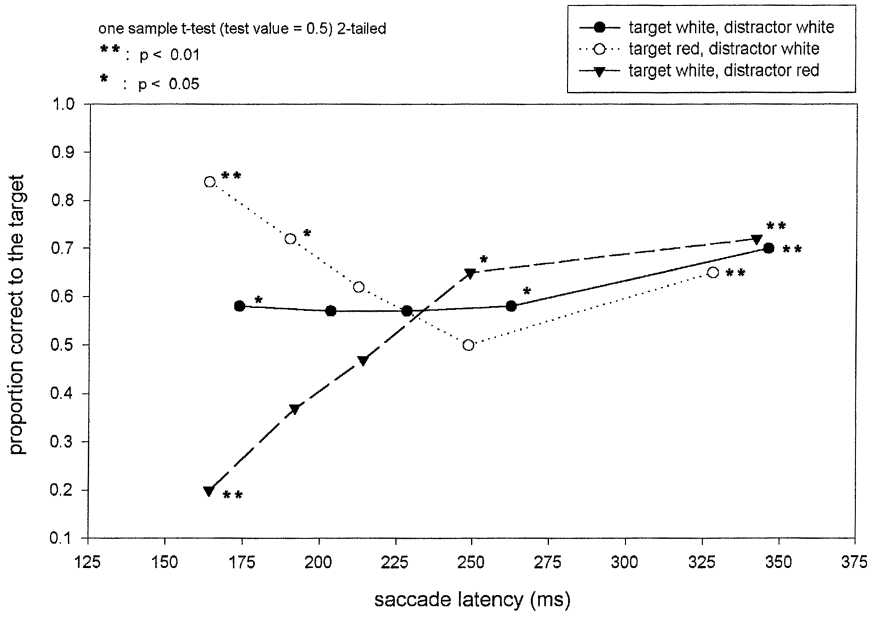

Figure 2. The proportion of saccades directed towards the target (right tilted elements) as a function of time. There were three possible conditions: Target, distractor, and nontargets were all presented in the same colour (no-colour singleton); only the target was coloured red (i.e., target-colour singleton); or only the distractor was coloured red (i.e., distractor-colour singleton).

the change in proportion of correct eye movements as function of quintile was different for the three different conditions.

Separate ANOVAs were performed on the proportions of correct saccades for each colour singleton condition with quintile (5) as factor. In the target-colour singleton condition, a main effect of quintile was found, $F(4, 44) = 5.50$, $p < .01$. Performance significantly decreased as a function of quintile in the target-colour singleton condition. In the no-colour singleton condition, performance increased as a function of quintile, $F(4, 44) = 4.95$, $p < .01$. In the distractor-colour singleton condition, performance also increased as a function of quintile, $F(4, 44) = 21.02$, $p < .01$.

Comparing the proportion of correct eye movements in each colour singleton condition per quintile, separate ANOVAs were performed for each quintile with colour singleton condition (3) as within factor. Significant differences were found in the first quintile, $F(2, 22) = 29.93$, $p < .001$, and the second quintile, $F(2, 22) = 4.72$, $p < .05$, but not in the third quintile, $F(2, 22) = 1.00$, $p > .05$. Significant differences between conditions were found again in the fourth quintile, $F(2, 22) = 3.82$, $p < .05$, but not in the fifth quintile $F(2, 22) < 1$.

Discussion

Experiment 1 has two major results. First, the presence of a colour singleton had a large effect on search performance. Overall performance was best when the target was presented as a colour singleton, followed by performance in the no-colour singleton condition. Search performance was worst in the distractor-colour singleton condition. Saccade latency toward the target was lowest in the target-colour singleton condition, followed by saccade latency in the no-colour singleton condition. Saccade latencies were highest in the distractor-colour singleton condition. Second, the results showed a discrepancy in the proportion of correct saccades towards the target between the fastest and the slowest saccades. Large effects of presence of colour singleton were found early during processing, while no effects were found later during processing (20% slowest eye movements). Somewhat surprisingly, while performance in the colour target singleton condition was high for the lowest saccadic latencies, performance sharply decreased as saccadic latencies increased. Performance in the target-colour singleton condition was seen to increase again only when saccadic latencies were higher than 250 ms.

While the average results (i.e., overall proportion and saccadic means) are in line with most current bottom-up models on visual selection (Cave & Wolfe, 1990; Itti & Koch, 2000; Koch & Ullman, 1985; Theeuwes, 1991, 1992, 1994; Wolfe, 1994; Wolfe et al., 1989), the results are not in line with a top-down control account of visual selection (e.g., Findlay, 1997; Findlay et al., 2001, 2002; Folk & Remington, 1998). Even though saliency was completely irrelevant to the observer's goals and intentions, saliency substantially affected performance.

Moreover, both bottom-up control and top-down control accounts of visual selection have troubles explaining the way in which search performance evolves as a function of time. When we look at the results as a function of saccade latency, bottom-up models of attention selection are able to account for the early effects of saliency, and top-down models of attention are able to account for the absence of an effect of saliency later during selection. In turn, a bottom-up account fails to explain the absence of a saliency effect in case of the slower eye movements, while a top-down control account fails to explain the large effect of saliency in case of the fast eye movements. The results of Experiment 1 support the independent selection model, where stimulus-driven control occurs before goal-driven control, yet both proceed independently operating in different time windows. According to the independent selection model (van Zoest et al., 2004), visual selection is initially completely stimulus driven. As a consequence, fast responses (or saccades with a short latency) are purely stimulus driven. After a minimal amount of time stimulus-driven activation is believed to decline and simultaneously visual selection is believed to become increasingly more goal driven. As a result, slow responses (or saccades with a relative long latency) are

primarily goal driven. Even though the independent selection model bears much resemblance to bottom-up models of visual selection (i.e., both types of models assume that visual selection is initially completely stimulus driven and that top-down control comes into play at a later point in time), it differs fundamentally with respect to the assumed relationship between bottom-up and top-down control. Whereas bottom-up models implicitly assume that top-down selection is conditioned upon stimulus-driven selection, an independent selection model does not assume such a contingency. Instead, mechanisms responsible for bottom-up and top-down selection are assumed to operate independently from each other. If observers emit a response late in time, stimulus-driven control is assumed to be declined (e.g., Nakayama & Mackeben, 1989) with the result that responses can no longer be stimulus driven. The results of the present study indeed suggest that this is the case: saliency did not contribute to a higher level of performance when saccade latency was larger than approximately 250 ms. Moreover, in the target-colour singleton condition, performance even declined as a function a saccade latency. Apparently, the assumed bottom-up advantage of the target in this condition did not seem to help performance in case of slower eye movements.

Even though the results of Experiment 1 are in line with the idea that bottom-up activation declines as a function of time, alternatively it is possible that observers were actively involved in inhibiting locations containing red. That is, the present results might also be accounted for by a bottom-up model where it assumed that upon detection of the most salient location, subjects became actively involved in inhibiting those locations (in this case the locations containing the feature ''red''). Because the colour red was not indicative of the target location and led to incorrect responses in one third of all trials (i.e., irrelevant-colour singleton distractor), participants could have chosen to actively try to ignore the colour red. In other words, participants could have attempted to actively inhibit bottom-up signals arising from the colour representations and to permit only orientation-based representations to guide attention (Yantis & Egeth, 1999). This top-down inhibition may have led to the absence of salience effects for the longer latencies and decreasing performance as a function of latency in cases where the target was presented as a red colour singleton. Experiment 2 was designed to test whether the absence of stimulus-driven selection during later processing was due to participants being actively involved in inhibiting a colour feature value or was due a passive decline in bottom-up activation.

EXPERIMENT 2

Experiment 2 was an exact replication of Experiment 1 with one difference: The colour of the distractor in the distractor-colour singleton condition was green instead of red. This resulted in three different conditions: In the target-colour

singleton condition, the target singleton was red, whereas the distractor was white; in the no-singleton conditions, both the target and the distractor were white; and in the distractor singleton condition, the distractor was green, whereas the target was white. The nontargets were white in all conditions. If the decrease in performance in the target-colour singleton condition in Experiment 1 was due to contingent top-down inhibition of the colour red, no decrease in performance should be seen in Experiment 2. Moreover, salience effects should be present irrespective of saccade latency. Participants should have no reason to top-down inhibit the feature value red since the colour red never indicated an incorrect response. If the decrease in performance had been due to an automatic decline in bottom-up activation, as predicted by the independent selection model, performance should be identical to that obtained in Experiment 1.

Method

Participants. 12 students of the Vrije Universiteit Amsterdam participated as paid volunteers in 50 minute sessions. Participants ranged in age from 18 to 30 and all reported having normal or corrected-to-normal vision.

Stimuli and procedure. Except for the colour of the distractor, the stimuli and procedure were identical to those of Experiment 1. The distractor in Experiment 2 was a green line segment oriented 45° to the left (CIE x, y, coordinates of .300/ .599; 14.85 cd/m^2). Similar to Experiment 1, target–distractor saliency was varied across three conditions. Displays consisted of either (1) a white target and a white distractor, or (2) a red target (CIE x, y, coordinates of .609/ .344; 14.92 cd/m^2) and a white distractor, or (3) a white target and a green distractor. The colours red and green were matched for luminance. Participants were told colour was not indicative of the target location.

Results

Initial saccade latencies below 80 ms (anticipation errors; 9.8% of trials) and saccade latencies above 600 ms (0.3 % of trials) were counted as errors and were excluded from analysis. The initial saccade was assigned to a target or distractor if the endpoint of the initial saccade was within 3° of visual angle of the particular target or distractor position. Of the initial saccades 1% missed either the location of the target or the distractor and were not analysed further.

Table 2 presents the percentages and the saccade latencies of the saccades directed towards the target or distractor for each colour singleton condition. To examine the percentage of correct eye movements to the target, an ANOVA with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) as a factor was performed. A main effect of colour singleton condition was found, $F(2, 22) = 8.111$, $p < .01$. The fewest correct eye

TABLE 2
Percentage and saccade latencies (in ms) of the saccades directed towards the target or distractor in Experiment 2

	Condition		
Direction of eye movement	*Target white, distractor white*	*Target red, distractor white*	*Target white, distractor green*
To the target			
Percentage (%)	58.4	70.2	45.5
Saccade latency (ms)	246	226	256
To the distractor			
Saccade latency (ms)	226	235	204

movements to the target were made in the distractor-colour singleton condition (mean 46%), followed by the no-colour singleton condition (mean 58%). Accuracy was highest in the target-colour singleton condition (mean 70%). To examine the effect of colour singleton condition on saccade latency to the target an ANOVA was performed with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) as factor. A main effect of colour singleton condition was found, $F(2, 22) = 8.10$, $p < .01$. Saccadic latency to the target was lowest in the target-colour singleton condition (mean 226 ms), followed by the no-colour singleton condition (mean 246 ms). Saccadic latency to the target was highest in the distractor-colour singleton condition (mean 256 ms).

An ANOVA on saccadic latency to the distractor with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) revealed a main effect of colour singleton condition, $F(2, 22) = 19.48$, $p < .01$. Saccadic latency to the distractor was lowest in the distractor-colour singleton condition (mean 204 ms), followed by the no-colour singleton condition (mean 226 ms). Saccadic latency to the distractor was highest in the target-colour singleton condition (mean 235 ms).

In order to examine performance as a function of time more closely, the time course of the proportion of correct eye movements directed towards the target was analysed. For each participant, an individual distribution of the initial saccade latencies was calculated irrespective of the saccade destination. Distributions were divided into five quintiles based on saccade latency and the proportion of correct eye movements was calculated for each quintile. For each quintile the average saccade latency was calculated (see Figure 3). An ANOVA was conducted with colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) and quintile (5) as factor. A main effect of colour singleton condition was found, $F(2, 22) = 11.40$, $p < .01$, as well as an effect of quintile $F(4, 44) = 10.93$, $p < .01$. An interaction between

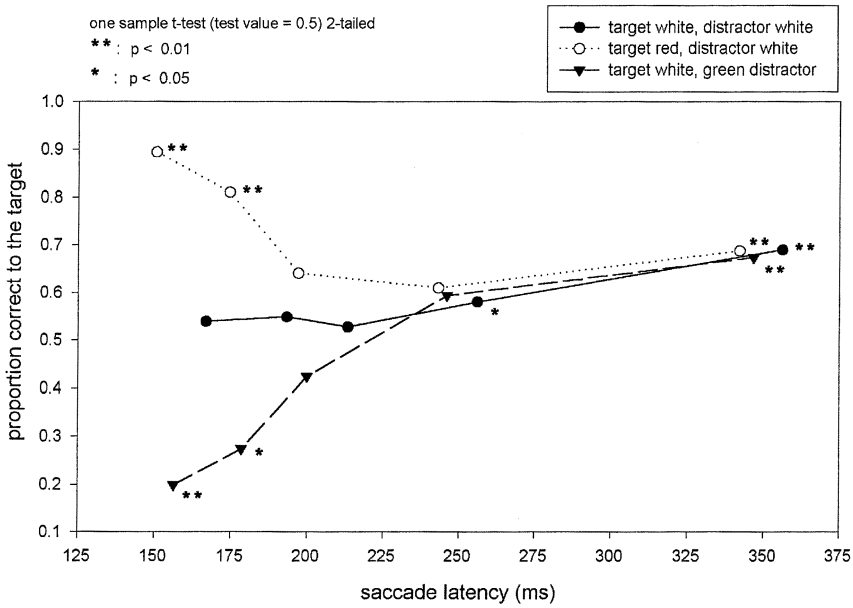

Figure 3. The proportion of saccades directed towards the target (right tilted elements) as a function of time. There were three possible conditions: Target, distractor, and nontargets were all presented in the same colour (no-colour singleton); only the target was coloured red (i.e., target-colour singleton); or only the distractor was coloured green (i.e., distractor-colour singleton).

colour singleton condition and quintile, $F(8, 88) = 11.57$, $p < .01$, indicated that the change in proportion of correct eye movements as function of quintile was different for the three different conditions.

Separate ANOVAs were performed on the proportions of correct saccades for each colour singleton condition with quintile (5) as factor. In the target-colour singleton condition, a main effect of quintile was found, $F(4, 44) = 4.91$, $p < .01$. Performance significantly decreased as a function of quintile in the target-colour singleton condition. In the no-colour singleton condition, performance increased as a function of quintile, $F(4, 44) = 5.98$, $p < .01$. In the distractor-colour singleton condition, performance also increased as a function of quintile, $F(4, 44) = 26.31$, $p < .01$.

Comparing the proportion of correct eye movements of each colour singleton condition per quintile, separate ANOVAs were performed per quintile with colour singleton condition (3) as within factor. Significant differences were found in the first quintile, $F(2, 22) = 32.25$, $p < .01$, and in the second quintile, $F(2, 22) = 11.03$, $p < .01$, but not in the third quintile, $F(2, 22) = 2.48$, $p > .1$, nor in the fourth quintile, $F(2, 22) < 1$, nor in the fifth quintile $F(2, 22) < 1$.

An ANOVA was conducted to compare the overall accuracy (percentage correct to the target) between Experiment 1 and 2. Experiment (1 and 2) was taken as a between factor and colour singleton condition (no-colour singleton, target-colour singleton, and distractor-colour singleton) and quintile (5) were taken as within factor. No effect of experiment was found, $F(1, 22) < 1$. No interaction was found between experiment and colour singleton condition, $F(2, 44) < 1$, nor between experiment and quintile, $F(4, 88) < 1$, nor between experiment, colour singleton condition, and quintile $F(8, 176) < 1$. No differences were found between the proportion of correct eye movements to the target obtained in Experiments 1 and 2.

Discussion

The results of Experiment 2 were identical to the results of Experiment 1. Relative to the performance in the condition where no-colour singletons were presented, performance was higher when the target was presented as a colour singleton, and performance was lower when the distractor was presented as a colour singleton. Relative to the saccade latency in the condition where no-colour singletons were presented, saccade latency to the target was lower in the target-colour singleton condition and was higher in the distractor-colour singleton condition.

As in Experiment 1, the results of Experiment 2 showed a large discrepancy in the proportion of correct saccades towards the target between the fastest and the slowest saccades. Large effects of saliency were found for the fastest saccades, while no effects of saliency were found for the slowest saccades (i.e., third, fourth, and fifth quintile). More importantly, performance in the target-colour singleton condition was seen to decrease as a function of saccade latency. Similar to Experiment 1, performance in the target-colour singleton condition was high for the fastest eye movements; performance sharply decreased as a function of saccade latency and started to increase again only for saccade latencies higher than 250 ms.

The results of Experiment 2 demonstrate that participants did not seem to be actively involved in inhibiting the colour red as predicted by a bottom-up model of visual selection. Instead, the results support the view that visual selection is determined by two independent processes, one fast process that is stimulus driven and a second slower goal-driven process.

GENERAL DISCUSSION

The present study investigated the role of saliency during saccadic target selection. The aim was to determine how bottom-up and top-down control affect visual selection. The results of Experiments 1 and 2 showed that the effects of saliency were large early during the processing while no effects of saliency were found at all later during processing. These results provide full support for the

independent selection model. The findings in the present study are difficult to reconcile with both a top-down and a bottom-up account of visual selection.

According to top-down models (Bacon & Egeth, 1994; Folk & Remington, 1998; Folk et al., 1992, 1994), visual selection should initially be completely goal driven. The results of the present study demonstrate that this was not the case. Initial selection appeared to be largely stimulus driven. Even though, the colour singleton was completely irrelevant to the task, observers were not able to ignore it. If observers would have been able to select only those elements that were relevant to the task, colour singleton condition should not have affected performance.

Nevertheless, a top-down account of visual selection may be able to account for our results if one assumes that participants adopted different strategies within blocks of trials. According to Bacon and Egeth (1994), observers may choose to rely on a mode of processing that identifies elements that differ from their backgrounds, a singleton detection mode, or may choose to monitor a specific feature, referred to as feature detection mode. Irrelevant feature singletons may or may not cause distraction during search for a known target, depending on the search strategy employed: Only when people are tuned to the singleton detection mode will irrelevant salient distractors hinder search performance (Bacon & Egeth, 1994). Thus, one could infer participants to have adopted a singleton detection mode in cases of fast responses and to have adopted a feature-search mode in cases of slow responses. In turn, only fast responses showed interference from a salient distractor while slow responses did not. While this account is in line with the data presented, it involves circular reasoning (Lamy & Egeth, 2003). In contrast to the idea that observers may voluntarily choose to be engaged in one or the other mode, it is possible that a singleton detection mode is initially mandatory, possibly followed by a feature search mode. Similarly, Lamy and Egeth have speculated a singleton detection mode to prevail early on while a feature search mode dominates during later stages of selection. These last alternatives, however, should no longer be considered top-down accounts of selection, as the selection modes cannot be adopted in a truly voluntary manner and are too stringently coupled to response times.

Bottom-up models of visual selection (Itti & Koch, 2000; Nothdurft, 2002; Theeuwes, 1991, 1992, 1994) assume that observers are initially driven by the relative salience of elements in the visual field. Accordingly, initial visual selection is assumed to be identity- blind and based only on the presence of a salience signal at a certain location in space. Identification of a stimulus is possible, however, only after it has been selected on the basis of its salience properties. That is, the identification of an element is assumed to be conditioned on whether it has been selected on the basis of its salience (e.g., Nothdurft, 2002). As a result top-down control is also assumed to be conditioned upon stimulus-driven selection. The results of the present study are not in line with this idea. Even though, the results of both Experiments 1 and 2 demonstrate that

visual selection is initially indeed completely salience driven, the results also demonstrate that this advantage disappears later in time, i.e., if saccade latency increases, performance is independent of salience. Moreover, if the target is the most salient element in the display, saccadic target selection is very accurate for fast saccades, but accuracy drops sharply if saccadic latencies become higher. A bottom-up view may account for the results of Experiment 1 by assuming that upon detection of the most salient location, subjects were able to quickly identify the colour feature, resulting in the application of inhibition if the feature value was red. In Experiment 1, the colour red was not indicative for the target location rendering such a strategy likely. However, in Experiment 2, if present, the colour red was always indicative for the target location. If observers would have identified the target upon selection of the colour red, performance in the target-colour singleton condition should not have become worse as a function of saccadic latency. The results showed that this was not the case. Like in Experiment 1, performance in the target-colour condition declined significantly if saccadic latency increased. Moreover, again, salience effects disappeared when saccadic latency increased. This suggests that stimulus-driven selection occurs early whereas identity-based selection processes occur at a later point in time. Furthermore, the results showed that late identity-based selection does not profit from accidental target saliency.

At this point it is important to note that previous studies have demonstrated identification processes to profit from salience. For example, in a study carried out by Nothdurft (2002), participants were asked to indicate the location and the orientation of a salient line segment. The saliency of the target line segment was manipulated by either increasing its luminance, making the line segment move, or by drawing a circle around it. The results showed that salient elements were not only detected quicker, but were also more quickly identified than less salient elements. Nothdurft's findings seem to be in conflict with the current results. However, it is important to note that, in Nothdurft's study, saliency information was explicitly task-relevant. That is, observers knew that the most salient element always corresponded to the target irrespective of its feature values. This was not the case in our study. Salience was not related to the target. Apparently, if available, saliency can be used to accomplish rapid detection and identification. However, if task demands explicitly instruct observers to search for a certain identity (as in the present study) saliency may only be beneficial during a limited period of time. Under such conditions, it becomes evident that bottom-up activity is not a necessary prerequisite for top-down selection. Thus, when in a visual search task a target can only be found on the basis of its identity, an accidental high target salience may initially enhance performance, however, the advantage of target saliency disappears later on.

In line with the idea that target salience is not always be beneficial to search, Yantis and Egeth (1999) showed that when target and salience coincide only rarely, response time depended little on whether the target was

salient. In a manual response task participants were asked to report the presence of a vertical line element among tilted nontarget elements rotated either 30° to the right or left of vertical. The task was attentionally demanding as response times increased linearly with display size. A colour singleton was presented on every trial, but the target coincided with the singleton only a small portion of trials. The results showed that responses times were no faster for singleton targets than for nonsingleton targets (Yantis & Egeth, 1999). The finding that accidental saliency did not affect search performance in the Yantis and Egeth study is not in agreement with the findings of the present study in that we did find an overall advantage for when the target is presented as a colour singleton. Nevertheless, the results of the present study are in line with the results reported by Yantis and Egeth if one only considers the results of the slower saccadic responses found in the present study. These slower saccadic responses showed no effect of target salience. The discrepancy between the two studies may be explained by the difference in response times observed in the studies. The overall saccadic latencies reported in the present study are much lower (i.e., mean 250 ms) than the manual response times reported by Yantis and Egeth (i.e., mean 750 ms). Previous work shows that timing is a critical issue in determining whether visual selection is largely stimulus driven or goal driven (see Ludwig & Gilchrist, 2002; van Zoest et al., in press). Ludwig and Gilchrist have shown that relative slow manual responses were much less affected by distractor onset than were relative fast eye movements. Furthermore, one could speculate that attentionally demanding search resulting in slow manual response times will be much less affected by stimulus-driven salience manipulations as compared to fast and easy search (see Lamy & Tsal, 1999).

The results of the present study support the independent selection model, where stimulus-driven control occurs before goal-driven control both proceeding independently and operating in different time windows. The independent selection model maintains that visual selection is initially completely stimulus driven. Early stimulus-driven activation is believed to rapidly decline as a function of time. Indeed, several studies have shown that stimulus-driven, bottom-up activation decays over time (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989; Nothdurft, 2002; Yantis & Jonides, 1990). For example, Nakayama and Mackeben (1989) showed that perception of an odd target in a conjunctive display was improved by transient cueing. Moreover, perception of the odd target was best when the cue preceded the target display by 70–150 ms. Longer delays led to a marked downturn in performance. Furthermore, this transient attentional component was independent of observer's prior knowledge and was not subject to voluntary control. The results of studies like these (see also Cheal & Lyon, 1991; Müller & Rabbitt, 1989) suggest that bottom-up activation as a consequence of a peripheral cue is transient and dissipates within a few hundred milliseconds (Kim & Cave, 1999).

However, it should be noted that alternatively, observers may have a mechanism at their disposal to actively inhibit stimulus-driven activity under conditions in which saliency information is explicitly irrelevant. This active inhibition of saliency may also have resulted in the decline in stimulus-driven activation as a function of time. While the results of Experiment 2 showed that participants were not actively inhibiting the colour feature value red, it is still possible that participants were actively inhibiting saliency as such. It is possible that participants were inhibiting any salient object that could possibly interfere with their search for the correct orientation identity. Evidence suggests that top-down control may actively inhibit bottom-up activity triggered by irrelevant salient elements. In the field of oculomotor selection, Tipper (2000) has argued that inhibition may be achieved through reactive inhibitory feedback loops, in which the strength of inhibition depends on the strength of the activation state: Elements that elicit a great deal of saccade-related activity will be inhibited more than elements that elicit less saccade-related activity (see also Godijn and Theeuwes, 2004). If top-down inhibition on the location of the salient element starts early enough, an eye movement based strictly on bottom-up activation can still be prevented. If top-down inhibition starts late, the eyes will be drawn to the location of the salient element.

While active inhibition of salient elements makes sense in cases where the salient element involves a distractor item (e.g., Godijn & Theeuwes, 2004), active inhibition does not make sense in case the salient elements involves the target. It seems counterintuitive to assume that activation at the target location is inhibited when the activation is working in favour of performance like was the case in the colour singleton target condition. However, it is possible that prior to the application of top-down inhibition, the element was not identified. Due to bottom-up activation at the location of the salient element (either the target or the distractor), the eyes possibly were triggered to move before the identity issue was resolved. In both the field of attentional and oculomotor selection, salient events have repeatedly seen to capture the eyes (Godijn & Theeuwes, 2002; Itti & Koch, 2000; Kramer, Cassavaugh, Irwin, Peterson, & Hahn, 2001; Theeuwes, 1991, 1992; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). Theeuwes (1992) showed that focal attention is attracted to the location of the feature that ''pops out'' first, irrespective of whether that feature is a target or distractor. Indeed, the lack of selectivity early in visual processing suggests that identification has not yet taken place (Theeuwes, 1992). While salient items were detected early in time, identification happened at later stage (see VanRullen, 2003). It might have been the case that the mechanism of active inhibition kicked in before the identity issue was resolved. In order to make a correct eye movement, participants might have been actively inhibiting salient elements in the display. It is possible that, in case the target was a salient element (i.e., colour singleton target), participants were actively inhibiting the location of the target.

Both the idea of passive decay of bottom-up activation (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989; Nothdurft, 2002; Yantis & Jonides, 1990) and the idea of active inhibition of saliency signals (e.g., Godijn & Theeuwes, 2004; Theeuwes et al., 1998) may explain why stimulus-driven bottom-up activation declines as a function of time. The results of the current study are not conclusive as to whether the decrease in stimulus-driven activation was due mainly because of passive decay of stimulus-driven activation or because of active inhibition of detected saliency signals, or was due to both mechanisms acting collectively. Further research should investigate this matter.

Regardless of the exact mechanism underlying the decrease in performance in the target singleton condition, performance for the late responses was less accurate than performance for the early responses. A possible explanation for these results may be that different activation levels were present early and late during processing. More specifically, it may be that the amount of stimulus-driven activation during early processing was much higher than the amount of goal-driven activation later during processing. If one assumes that the level of activation at a given location indirectly indicates the level of accuracy attainable, then one may assume that in cases of fast responses to a very salient target, the high level of bottom-up activation will lead to a high level of accuracy. If, however, the target and distractor are similar and discrimination between target and distractor is difficult, the lower level of top-down activation at the location of the target will make it more difficult to elicit a correct response and in turn will lead to a decreased level of accuracy. In addition, others have shown that accuracy levels obtainable on the basis of stimulus-driven activation are higher than the levels attainable under goal-driven conditions (see Nakayama & Mackeben, 1989).

The independent selection model maintains that the role of top-down control in visual selection appears to be independent of stimulus-driven control and limited to later points in time. Central cueing studies show it takes time for voluntary attention develop at a certain location (e.g., Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). For example, in a study by Müller and Rabbit (1989), observers had to indicate the orientation of a T presented in one of four peripherally presented boxes. The presentation of the boxes was preceded by a valid or invalid peripheral or central location cue, and stimulus–onset asynchrony (SOA) between cue and search display was varied. The results demonstrated that facilitation and inhibition of activation from peripheral and central cues were characteristically different. While the effects of peripheral cues were fast and transient (<175 ms), the effects of central cues were slow and sustained (>400 ms). The results of this study suggest that top-down activation (as elicited by a central cue) does not only occur at a later point in time than bottom-up activation (as elicited by a peripheral cue) but has a different time-course also (Müller & Rabbitt, 1989). The results of studies like these (e.g., Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama &

Mackeben, 1989), and the results of the current study suggest that goal-driven selection takes more time than stimulus-driven selection.

The results of the present study have implications for current models of visual selection. The results of our study are not in line with the Guided Search (Cave & Wolfe, 1990; Wolfe, 1994) model of visual selection, in that we have found that bottom-up and top-down activation did not summate. Our results do not, however, necessarily contradict models of visual selection that assume some form of top-down modulation. However, it appears that top-down modulation can take place only late in the selection process. Top-down modulation of bottom-up activation might vary depending on whether or not saliency information is task-relevant or not (see also Nothdurft, 2002).

The results of the present study show that performance is best when the target is the most salient item in the display. However, our results show that when observers are really required to search for an identity, observers are not able to use the saliency information in a goal-driven manner. Going back to our library example, when you are trying to find a book by title or author and when the book turns out to be bright red and very large, you might be lucky and accidentally find the book quickly based on its salient features. However, if you do not find the book based on its salient features immediately and must start to find the book truly based on the title and author, you no longer seem to be able to use the saliency information to your advance.

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